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Studies on compressive strength of sand stabilized by alkali-activated ground bottom ash and cured at the ambient conditions

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Abstract

Background: Bottom ash is a by-product generated during the coal combustion of thermal power plant. Bottom ash-based geopolymer has been reported as a promising substitute of cement in concrete.

Methods: In this study, bottom ash collected from Honam Coal Power Plant was ground to be used as a soil stabilizer. Sodium hydroxide solution (NaOH) with different molarity concentration and sodium silicate solution (Na_2SiO_3) were added to enhance the polymerization reaction of ground bottom ash. The effects of water/ground bottom ash, Na_2SiO_3/NaOH ratio and concentration of NaOH solution on the unconfined compressive strength of sand mixture at the ambient curing conditions were investigated.

Results: The results indicated that ground bottom ash can be utilized to stabilize sand as a main binder at the ambient curing conditions. In particular, with the 4 M concentration of sodium hydroxide solution, the Na_2SiO_3/NaOH ratio of 1.5 and the water/binder ratio of 0.35, the highest compressive strength obtained at 28 days was around 9 MPa.

Conclusions: The compressive strength of sand mixture increased with an increase of NaOH solution concentration and the ratio of Na_2SiO_3/NaOH, however, it dramatically decreased with the addition of water to the mixture.

Keywords: Compressive strength, Ground bottom ash, Alkaline activator, Sand, Ambient condition

Background

Nowadays, cement plays an important role in the construction industry. According to statistics, the production of cement in the world increased from 3310 million metric tons in 2010 to 4100 million metric tons in 2015 [22], http://www.statista.com. However, the production of cement creates some environmental issues especially such as CO_2 emissions causing the greenhouse effects. It is estimated that corresponds to one ton of cement produced, one ton of CO_2 will be emitted into the atmosphere [19]. The cement production contributed about 7 % of the total greenhouse gas emissions to the earth's atmosphere [20]. In the efforts to solve these issues many studies to find out the alternative material to substitute cement have been published [3, 11, 14, 16, 18]. One of the new alternative materials which can be used to replace cement is geopolymer materials.

The term "geopolymer" was first introduced by Joseph Davidovits in 1978 [8]. Geopolymers are formed by reacting silica-rich and alumina-rich solids with an alkaline solution, resulting in a mixture of gels and crystalline compounds that eventually harden into a new strong matrix [23]. Depending on the raw material characteristics and processing conditions such as curing conditions, alkaline concentration and types of alkali cations, geopolymers can exhibit a wide variety of properties and characteristics, including properties of cementitious materials and adhesives, high compressive strength, fire resistance, and low thermal conductivity [10]. Using geopolymer materials have great significance for the environment. It is not only reduce greenhouse gas emissions but also consume large volumes of industrial wastes [17]. In general, the two main ingredients involve in the formation of geopolymer are the aluminosilicate binder and alkali activating agent. The binders are composed of high aluminosilicates contain such as slag, fly ash, rice-husk ash while the alkaline activating agents are compounds of alkali metals (NaOH, KOH).

Fly ash and bottom ash are waste materials generated from coal-fired thermal power plants. As mentioned above fly ash is being widely used to manufacture the geopolymer materials [4, 13, 20]. Meanwhile, except in some countries where bottom ash is used as a low-cost replacement for more expensive sand in the production of concrete blocks and a base in road construction [12], most of it is disposed in landfills and caused environmental pollution. However, based on the X-ray fluorescence test results (Table 1), it can be found that bottom ash and fly ash have similar chemical compositions. The XRD patterns of bottom ash (Fig. 1) also indicated that its crystalline phases are predominantly quartz and mullite which represent for silica and alumina—two main gradients to form geopolymer. Therefore, by grinding to reduce particle size, bottom ash can be used as a pozzolanic material that was repoted by Jaturapitakkul and Cheerarot [15].

Table 1 Chemical composition of ground bottom ash and fly ash (% by weight)

Component	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	TiO_2	K_2O	Na_2O	LOI
Ground bottom ash	1.80	62.53	20.91	0.69	8.70	1.28	1.44	0.39	1.85
Fly ash	1.99	56.88	21.52	0.92	6.34	1.21	1.58	0.49	8.73

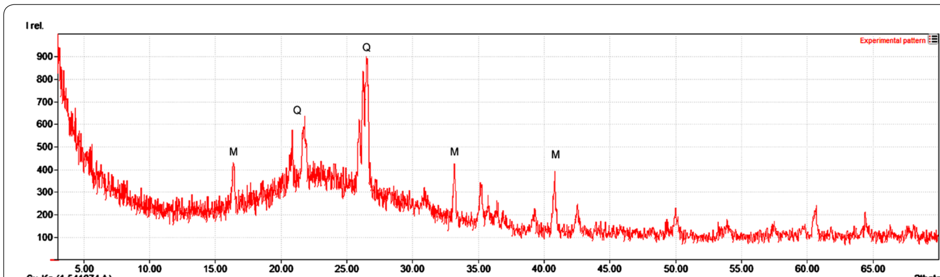


Fig. 1 XRD spectra of bottom ash (*Q* Quartz, *M* Mullite)

Currently, some researchers have used ground bottom ash as a partial replacement of cement or combined it with alkali activating agent to completely replace cement. The most common alkaline activator used in geopolymerisation is a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate or potassium silicate [9]. In general, the geopolymer mortar is prepared with a high concentration of NaOH solution (10 M) and specimens are cured at the high temperature (65 °C for 48 h) to achieve higher compressive strength of over 20 Mpa [7].

This study focuses on the assessment of the compressive strengths of sand mixtures which were stabilized by alkali-activated ground bottom ash prepared with low concentration of NaOH solution and cured at the ambient conditions. It would lay a foundation for the future utilization of ground bottom ash as a valuable resource of stabilizing soil for sustainable infrastructure constructions instead of treating bottom ash as a waste material.

Experimental program

Materials

Bottom ash was collected from Honam thermal power plant and dried to completely loss of moisture content. To grind bottom ash, a ball-grinding machine was used. The velocity of roller was kept at 120 round per minute and the diameter of 40 mm of ball was selected. After grinding, bottom ash fineness was checked complying standard ASTM C204 [1]—the test methods for fineness of hydraulic cement by air-permeability apparatus. The test result showed that after 3 h of grinding the fineness of ground bottom ash was 2000 cm^2/g. Even though it is still coarse in comparing with Portland cement (3600 cm^2/g) and fly ash (3000 cm^2/g) [6], a fineness of 2000 cm^2/g is enough to get a significant strength which was reported by Sathonsaowaphak et al. [21]. The effectiveness of grinding can be visualized in Fig. 2 and expressed in detailed via grain size distributions in Fig. 3. A scanning electron microscopy (SEM) test was conducted on raw and ground bottom ash to study surfaces and particles. At the same magnification, raw bottom ash exposed as large and very irregular particle shapes, containing high pores and cavities (Fig. 4a), meanwhile those of ground bottom ash were smaller and relatively uniform (Fig. 4b). Grinding process not only reduced the particle size and porosity but also destructed the grain structure of the material that facilitate the alkaline-activators to contact with aluminosilicate ingredients.

a Raw bottom ash **b** Ground bottom ash **c** Fly ash

Fig. 2 Particles of raw bottom ash, ground bottom ash and fly ash

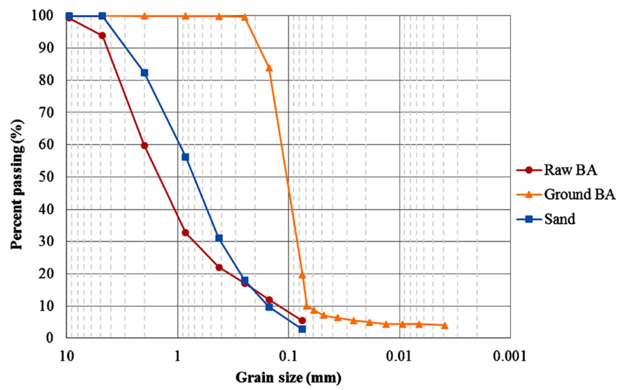
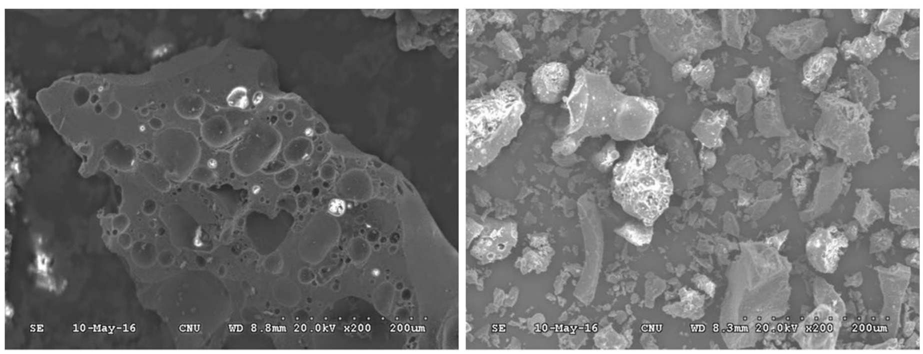


Fig. 3 Grain size distribution



a Raw bottom ash **b** Ground bottom ash

Fig. 4 Scanning electron microscope of raw and ground bottom ash

The alkaline activators used in this study were sodium hydroxide solution (NaOH) and sodium silicate solution (Na_2SiO_3). The sodium hydroxide is available in the form of pellets with 98 % purity. The sodium hydroxide solution was prepared by dissolving the pellets in distilled water. The mass of sodium hydroxide solid in a solution depends on the concentration of solution and it is expressed in terms of molarities. Sodium silicate solution was purchased directly from the company with a SiO_2/Na_2O molar ratio of 3.1 and the percentages by weight are 10 % of Na_2O, 30 % of SiO_2 and 60 % of water. Well-graded sand was used as a fine aggregate. Particle size distribution of sand was shown in Fig. 3 and other properties were given in Table 2.

Methods

At first, in order to evaluate the effect of NaOH solution concentration on compressive strength of stabilized sand, various molar concentrations of 2, 4, 6 and 8 M were

Table 2 Geotechnical properties of sand

G_s	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_u	C_c	USCS
2.64	0.15	0.41	1.02	6.6	1.08	SW

employed. While the liquid alkali activator/ground bottom ash ratio and the Na_2SiO_3/NaOH ratio of were fixed as 0.5 and 1.5, respectively.

Secondly, 4 M of concentration of NaOH solution was selected basing on the results of the first experiment. To assess the effect of water/ground bottom ash ratio on compressive strength of stabilized sand, the various amounts of water were added to the mixture. Other parameters as the liquid alkali activator/ground bottom ash ratio and the Na_2SiO_3/NaOH ratio were still kept as 0.5 and 1.5, respectively.

Finally, the Na_2SiO_3/NaOH ratio was varied from 0.5 to 2.5 to assess the effects of Na_2SiO_3/NaOH ratio on compressive strength and to find out the optimum ratio. Meanwhile, the liquid alkali activator/ground bottom ash ratio of 0.5 were kept.

Ground bottom ash was first mixed with NaOH solution and Na_2SiO_3 solution for 10 min to allow the leaching of ions. Sand was mixed with the ground bottom ash with a ratio of 3:1 and extra water was added if needed. Thereafter, fresh mixtures were cast in the cylindrical molds ($\phi = 50$ mm, h = 100 mm). Based on the test method for laboratory compaction characteristics of soil [2], fresh mixture in the mold was divided into three layers and compacted with 25 blows of rammer for each layer. Finally, molds were immediately capped to prevent moisture loss. All specimens were demolded after 24 h and then cured at the ambient condition (50 % humidity and 15 °C). Compressive strengths of specimens were measured at the ages of 7, 14, 28 days.

Results and discussion

Effect of NaOH solution concentration

Figure 5 shows the effect of concentration of NaOH solution on the compressive strength of sand mixture stabilized with the alkali-activated ground bottom ash. It can be observed that the setting process has been delayed with the increase of concentrations of NaOH solution. At 7 days, sand mixture prepared with lowest concentration of NaOH solution (2 M) achieved 2.6 MPa of compressive strength meanwhile that of highest concentration case (8 M) just achieved 1.2 MPa. However, the trend was reversed shortly thereafter, sand mixture improved with higher concentration of NaOH showed a faster rate of gain of strength. The final results indicated that the compressive strength slightly increase with the increase of NaOH solution concentration. The highest compressive

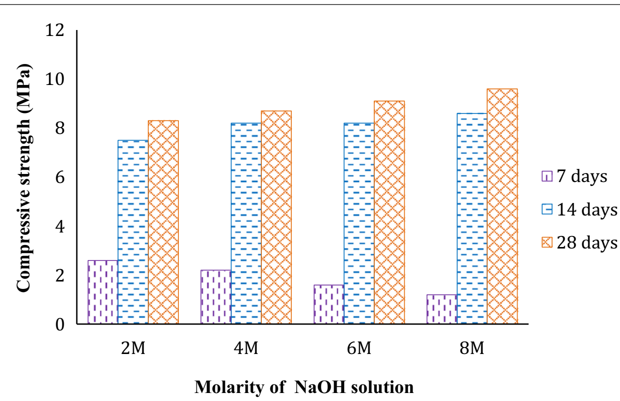


Fig. 5 Compressive strength of stabilized sand at various molarities of NaOH solution

strength obtained at 28 days by using the highest concentration of sodium hydroxide was approximately 10 Mpa.

This phenomenon is similar with other previous studies of Chindaprasirt et al. [7], Sathonsaowaphak et al. [21], and Hanjitsuwan et al. [13]. Chindaprasirt et al. [7] showed that the strength increased with the increase of NaOH concentration mainly because of the amount of leaching of silica and alumina ions and resulted in a high degree of geopolymerization. In another study performed by Chindaprasirt and Chalee [5] involving the chloride penetration of geopolymer concrete, the authors have pointed out that an increase NaOH solution concentration in geopolymer concrete resulted in a low porosity of paste and an increase in the compressive strength.

Based on this case study, alkaline-activated ground bottom ash prepared with low concentration of NaOH solution has demonstrated the ability to stabilize sand at the ambient temperature curing condition. In addition, it can also be observed from Fig. 5 that with 2 M of NaOH solution concentration, the compressive strength of stabilized sand is relatively high. However, a concentration of 4 M was selected for the further experiments to ensure the attainment of high strength when concentration of solution will be significantly reduced by adding water.

Effect of water/ground bottom ash ratio

In this case study, the ratio between the amount of water contained in alkali solution and ground bottom ash was 0.35. By adding various amounts of water to the mixture, the effect of water/ground bottom ash ratio was studied. It can be seen from Fig. 6 that the compressive strength rapidly decreases with the increase of water amounts. In the case of absence of added water the compressive strength is 8.7 MPa while the lowest compressive strength is 4 MPa corresponding to the water/ground bottom ash ratio of 0.65.

The main reason of the decrease of strength is excess water, which is diluted the liquid and thus slowed down the dissolution and reaction of the geopolymerization process. Another reason is that extra water reduces the efficiency of compaction, which cause high porosity in the specimens.

The variation of compressive strength corresponding to the ratio of water and ground bottom ash is one of the key parameters in design of sand stabilization. From the value of water content of sand material collected in the field, engineers can estimate the amount

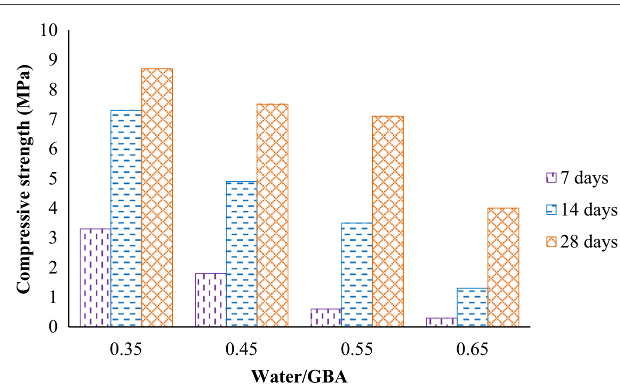


Fig. 6 Compressive strength of stabilized sand at various water/ground bottom ash ratios

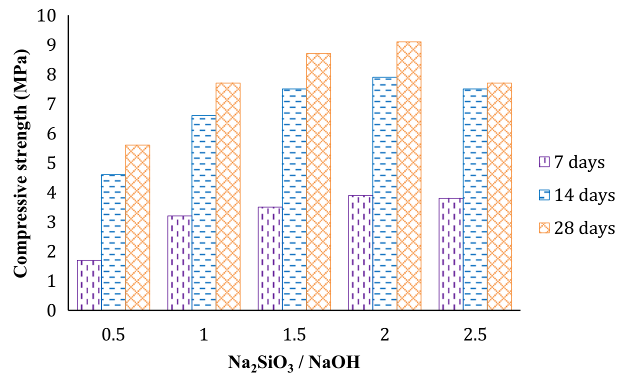


Fig. 7 Compressive strength of stabilized sand at various Na_2SiO_3/NaOH ratios

of binder needed to produce a desired strength by comparing with the results indicated in Fig. 6.

Effect of Na_2SiO_3/NaOH ratio

The effect of Na_2SiO_3/NaOH ratio on compressive strength of sand mixture is shown in Fig. 7. The experimental results showed that the compressive strength increased with the increase of Na_2SiO_3/NaOH ratio from 0.5 to 2. The highest compressive strength was 9.1 MPa corresponding with the Na_2SiO_3/NaOH ratio of 2. The development of compressive strength is the result of the increase of SiO_2 content leached from Na_2SiO_3 solution. Similar explanations found in previous study of Xu and Van Deventer [24] indicated that the higher amount of sodium silicate improves the reaction rate and thereby develops long chain polymerization when compared to sodium hydroxide. However, when the Na_2SiO_3/NaOH ratio was 2.5, the strength started to decrease. This may be due to the greater amount of soluble silica in sodium silicate solution reduced the geopolymerisation reaction. In a similar phenomenon, Sathonsaowaphak et al. [21] explained that it is due to the difficulty in compaction.

Conclusions

At the ambient curing conditions, alkali-activated ground bottom ash can be effectively used as a binder and it achieves sufficient strength to apply for sustainable infrastructure constructions. The factors which can affect to the compressive strength of stabilized sand were investigated. Based on the obtained data, the following conclusions could be derived.

1. By grinding the bottom ash and activating it with optimized amount of NaOH and Na_2SiO_3, sand can be stabilized sufficiently in early age and compressive strength of sand mixture was increased up to around 10 MPa within 28 days even though cured in ambient condition.
2. The higher the concentration of NaOH, the higher the compressive strength of sand mixture. However, 2–4 M of NaOH is appropriate not only for the activating ground bottom ash for the geotechnical infrastructure but also for the economic benefit.

3. The increment of amount of water causes the rapid decrease of compressive strength of sand mixture. However, the compressive strength of 28 days was obtained as 4 MPa even though the amount of water in sand mixture is increased nearly double.
4. The compressive strength of sand mixture increases to a certain limit with the increase of Na_2SiO_3/NaOH ratio. The optimum of Na_2SiO_3/NaOH ratio is 2.

Authors' contributions

YSK gave ideas and participated in amending the manuscript. MQD and TMD participated in performing experiments, analyzing data, and drafting the manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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References

1. ASTM C204 (2016) Standard test methods for fineness of hydraulic cement by air-permeability apparatus, ASTM International, West Conshohocken, PA
2. ASTM D698 (2012) Standard test methods for laboratory compaction characteristics of soil using standard effort [12400 ft-lbf/ft^3 (600 kN-m/m^3)], ASTM International, West Conshohocken, PA
3. Cheerarot R, Jaturapitakkul C (2004) A study of disposed fly ash from landfill to replace Portland cement. Waste Manag 24(7):701–709
4. Chindaprasirt P, Chareerata T, Sirivivatnanonb V (2007) Workability and strength of coarse high calcium fly ash geopolymer. Cem Concr Compos 29(3):224–229
5. Chindaprasirt P, Chalee W (2014) Effect of sodium hydroxide concentration on chloride penetration and steel corrosion of fly ash-based geopolymer concrete under marine site. Constr Build Mater 63:303–310
6. Chindaprasirt P, Homwuttiwong S, Sirivivatnanonb V (2004) Influence of fly ash fineness on strength, drying shrinkage and sulfate resistance of blended cement mortar. Cem Concr Res 34(7):1087–1092
7. Chindaprasirt P, Jaturapitakkul C, Chalee W, Rattanasak U (2009) Comparative study on the characteristics of fly ash and bottom ash geopolymers. Waste Manag 29(2):539–543
8. Davidovits J, Comrie DC, Paterson JH, Ritcey DJ (1990) Geopolymeric concretes for environmental protection. Concr Int 12(7):30–40
9. Davidovits J (1994) Properties of geopolymer cements, First international conference on alkaline cements and concretes, Kiev State Technical University, Kiev, Ukraine
10. Duxson P, Fernandez-Jimenez A, Provis JL, Lukey GC, Palomo A, Van Deventer JSJ (2007) Geopolymer technology: the current state of the art. J Mater Sci 42:2917–2933
11. Elinwa AU, Mahmood YA (2002) Ash from timber waste as cement replacement material. Cem Concr Compos 24(2):219–222
12. Ghgafoori N, Cai Y (1998) Laboratory-made roller compacted concretes containing dry bottom ash: part I-mechanical properties. ACI Mater J 95(2):121–130
13. Hanjitsuwan S, Hunpratub S, Thongbai P, Maensiri S, Sata V, Chindaprasirt P (2014) Effects of NaOH concentrations on physical and electrical properties of high calcium fly ash geopolymer paste. Cem Concr Compos 45:9–14
14. Ismail MS, Waliuddin AM (1996) Effect of rice husk ash on high strength concrete. Constr Build Mater 10(7):521–526
15. Jaturapitakkul C, Cheerarot R (2003) Development of bottom ash as pozzolanic material. J Mater Civ Eng 15(1):48–53
16. Kim HK (2015) Utilization of sieved and ground coal bottom ash powders as a coarse binder in high-strength mortar to improve workability. Constr Build Mater 91:57–64
17. Majidi B (2009) Geopolymer technology, from fundamentals to advanced applications: a review. Mater Technol Adv Perform Mater 24(2):79–87
18. Naceri A, Hamina MC (2009) Use of waste brick as a partial replacement of cement in mortar. Waste Manag 29(8):2378–2384
19. Pacheco-Torgal F, Moura D, Ding Y, Jalali S (2011) Composition, strength and workability of alkali-activated metakaolin based mortars. Constr Build Mater 25(9):3732–3745
20. Shi XS, Collins FG, Zhao XL, Wang QY (2012) Mechanical properties and microstructure analysis of fly ash geopolymeric recycled concrete. J Hazard Mater 237–238:20–29
21. Sathonsaowaphak A, Chindaprasirt P, Pimraksa K (2009) Workability and strength of lignite bottom ash geopolymer mortar. J Hazard Mater 168(1):44–50
22. United States and world cement production in 2010 and 2015 (2016). http://www.statista.com/statistics/219343/cement-production-worldwide/
23. Verdolotti L, Iannace S, Lavorgna M, Lamanna R (2008) Geopolymerization reaction to consolidate incoherent pozzolanic soil. J Mater Sci 43(3):865–873
24. Xu H, Van Deventer JSJ (2000) The geopolymerisation of alumino-silicate minerals. Int J Miner Process 59(3):247–266